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# ATMOSPHERIC DENSITY DYNAMICS AND THE MOTION OF SATELLITES

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## ABSTRACT

The goal of our atmospheric density dynamics research is to understand and characterize the dynamic nature of the extreme upper atmosphere and develop improved orbital prediction algorithms based upon this new understanding. Many indicators suggest that the extreme upper atmosphere is far more dynamic than what is accounted for in atmospheric density models used in orbit propagation. This paper explores the impact these dynamics have on the motion of satellites. Simulations show that unmodeled atmospheric density dynamics can greatly impact the orbit determination process and add kilometers of error to orbit predictions.

## 1. INTRODUCTION

Atmospheric density modeling has long been one of the greatest uncertainties in the dynamics of low Earth satellite orbits. Accurate density calculations are required to provide meaningful estimates of the atmospheric drag perturbing satellite motion. These effects increase with lower altitude orbits and also with higher effective area and lower mass satellites. Both of these conditions are usually met by the new class of small satellites being developed around the world as low cost ventures into space.

Early atmospheric models were comprised of simple exponential functions with scale height factors, which allowed the user to estimate a constant density at a given altitude [1]. From these approaches and estimated density conditions, standard atmospheres were developed which were meant to represent the average conditions at any given point in time for a particular altitude. However, it was soon obvious that the atmosphere was far too dynamic to be adequately represented by static approaches.

The greatest contributor to the fluctuations in atmospheric density is the Sun. The Sun has two mechanisms for heating the atmosphere. The first is through direct transmission of radiation. This effect has been correlated to observed solar flux, typically measured at the 10.7 cm wavelength. Solar flux is usually measured once a day and reported as a global value. The second mechanism involves the release of charged particles into the atmosphere. These charged particles interact with Earth's magnetic field, allowing the amount of observed geomagnetic activity to be used as an indicator of atmospheric density. Geomagnetic activity is quantified by geomagnetic indices, which are reported as either averaged daily or 3-hour values.

For many years, the largest variation in solar activity has been traced to an approximately 11-year cycle, also known as the sunspot cycle. From the minimum to the maximum of the solar cycle, the solar flux triples in its average daily value. The peak of the solar cycle is also marked by increased geomagnetic activity. In addition to the 11-year solar cycle, the solar flux is also driven by a 28-day periodic effect due to the rotation of the Sun. An 11-day cycle has also been observed in the amount of geomagnetic activity. Although these cycles have been repeatedly observed, their nature is not sufficiently understood so that they can be predicted accurately. In fact, even the largest and most widely known effect, the sunspot cycle, is still not well predicted in terms of frequency or amplitude. The prediction of geomagnetic activity has been so poor that the NOAA Space Environment Center did not provide 3-day geomagnetic index predictions until recently.

One of the first steps towards including some of this variability into atmospheric density models was to construct static atmospheres for a variety of solar conditions. The Harris-Priester model represents one such approach where density look-up factors are tabulated in terms of solar flux conditions [2]. These improvements did provide better modeling but still treated the atmosphere as having constant density for a given altitude for a given period of time. The static models not only failed to account for changing solar conditions but also for the fact that the atmospheric density varies as a function of latitude and longitude which is also known as the diurnal effect caused by the Sun's uneven heating of the Earth's atmosphere.

In the late 1960s, Luigi Jacchia began developing a dynamic atmospheric density model, which takes into account all of the major effects described above and employs observed solar flux and geomagnetic indices as input into the model [3]. The model he published in 1970 (known as the Jacchia 70 model) has become somewhat of a standard in astrodynamics and is still in use by Air Force Space Command. Jacchia continued to refine his models but never markedly exceeded the accuracy of the original 1970 model. In the 1980s and 1990s additional dynamic atmospheric models such as the MSIS, GOST, and DTM series were developed using various principles of physics [4]. These models generally rely on the same solar flux and geomagnetic indices used by Jacchia as a measure of current solar activity. Even though the basis of the models are different, none have achieved a significant level of improvement over the Jacchia models, though studies have shown each model to perform better under certain circumstances than others. Generally, these state of the art models are considered to accurately model atmospheric density to around 15% of the actual values—a number that has not changed for 30 years [5].

The 1990s brought a new approach to improving atmospheric density modeling. Dynamic Calibration of the Atmosphere (DCA) involves estimating density corrections to a given atmospheric density model based upon the observed motion of satellites. The work of Marcos, Nazarenko and Cefola, and Storz are all examples of state of the art approaches to provide near real time corrections to atmospheric density models [6,7,8]. In each case, the observations from a group of satellites are used to estimate large scale corrections to an existing gravity model. Each of these studies has been examined in some detail with the work of Storz being most thoroughly investigated through an Air Force Battlelab demonstration program called the High Accuracy Satellite Drag Model (HASDM). In all cases, the approaches have shown the potential to provide a general improvement to their baseline atmospheric density model.

The DCA approaches have several drawbacks, however. First, the approaches are designed to run in real time and internal to a space surveillance architecture. This means that most users outside of the space surveillance architecture have to rely on that system to provide atmospheric density correction updates. Additionally, the atmospheric density corrections are only applicable to a certain point in time. Thus one must have access to the entire archive of density corrections in order to obtain meaningful information outside of the space surveillance application, and these archives may not exist for older time periods.

A second limitation of most DCA approaches is that the corrections do not improve upon the spatial and temporal resolution of the existing atmospheric density models. The corrections do allow the models to better represent the effects included in the models but do not address any higher order effects not included in the models. For instance, the Jacchia models assume the portion of the atmosphere that experiences the greatest diurnal heating effect is fixed in space relative to the Sun; this may not be true and is an example of a limit in spatial resolution of the Jacchia models. Most dynamic atmospheric density models use a daily solar flux and averaged 3-hour geomagnetic indices as input values for measuring of solar activity. Using these values limits the ability of the models to represent changes in the atmosphere that occur within the averaging interval of the input data. This is an example of a limit in temporal resolution. It should be noted that HASDM is experimenting with a spherical harmonic expansion based correction that may allow greater spatial resolution in their atmospheric density correction estimation.

Another limitation to DCA and non-DCA approaches alike is that they all treat the atmosphere as a discrete system based on the measurement intervals of the input proxy data. Input proxy data such as solar flux and geomagnetic indices are often input as constant values over their published measurement interval. The result is an atmosphere that is constant over the interval and discontinuous between previous and future intervals.

Given these limitations, DCA approaches are still powerful, and a great deal has been learned in their pursuit and implementation. Frank Marcos, a leader in the field, has described the present as "the Golden Age" of atmospheric density research for all of the quality work that has occurred over the past ten years. Among the findings the research community has made are the following:

- Input proxy data such as F10.7 cm solar flux and $a_p/k_p$ geomagnetic indices do not capture observed phenomena
- Atmospheric density model errors vary greatly by situation
- Atmospheric density dynamics are still more complex than physics-based models reflect
- Real time proxy data values are not the same as those archived

The first two issues are indicative of the third statement. The fourth is an artifact of one organization trying to determine real time values from one set of observations while the officially archived values are postprocessed by a different organization using a different set of observations. This research does not address the last issue, but it is included as a relevant problem.

The objective of this research is to explore currently unmodeled atmospheric density dynamics and their effects in both time and space. It is hypothesized that these effects do exist and are affecting the motion of satellites. If these effects can be observed, an effort will be made to derive theoretical links with known physical phenomena and, if successful, to incorporate these effects into atmospheric density models. How does atmospheric density change in both time and in space? How do these changes affect the motion of satellites? These are some of the fundamental questions that this research will address.

This research is relevant to the issues of the day in several ways. First, it is highly complementary to the DCA research projects. As previously stated, DCA is limited by the discrete estimation intervals and the discontinuities between these intervals. Members of the HASDM team have indicated that these discontinuities also limit their ability to use spherical harmonic spatial correction terms. This research can help mitigate or eliminate the effects of discontinuous data intervals if a proper understanding of how the atmosphere changes as a function of time and space is developed. This knowledge is also valuable for non-DCA approaches using existing atmospheric density models. Secondly, this research can be used to seed theoretical development of first principle physics-based atmospheric density theory. If this research provides links of the behavior of atmosphere to observed physical phenomena, it may help identify effects that are not currently modeled or understood but are driving atmospheric heating. Several indicators point to important unmodeled effects.

This paper summarizes the first phase of the atmospheric density dynamics research. The research is built on two fundamental hypotheses: 1) the atmosphere is much more dynamic than what is currently being implemented in orbit propagation theory, and 2) these atmospheric density dynamics observably affect the motion of satellites. The rest of this paper is dedicated to the support of these hypotheses.

## 2. ANALYSIS AND RESULTS

While it has recently been observed that F10.7 cm solar flux and the $k_p$ geomagnetic index do not adequately capture variations in atmospheric density, they have been used as input proxy data to atmospheric density models for decades. Due to their limitations, this may change as more advanced methods are developed, but as a first step in this research, continuous variations in F10.7 cm solar flux and the $k_p$ geomagnetic index are considered. It is anticipated that other atmospheric density drivers would likely exhibit similar variability since they would also be related to solar activity. The first part of this work focuses on the dynamics of these data, while the second investigates the impact that unmodeled atmospheric density dynamics could have on the motion of satellites.

### 2.1 The Variability Hypothesis

Since 1991, F10.7 cm solar flux has been measured three times daily at the Dominion Radio Astrophysical Observatory in Penticton, British Columbia, Canada. Measurements occur at 17:00, 20:00, and 23:00 hours Universal Coordinated Time (UTC). The 20:00 value, corresponding to local noon, is usually reported as the official measurement (though under some solar event circumstances, one of the other measurements may be delivered as the daily value) and stored by the National Oceanic and Atmospheric Association (NOAA) Space Environment Center and the National Geodynamics Data Center (NGDC). For atmospheric density modeling and orbit propagation, the observed value of solar flux is typically the one used and is held constant over the daily reporting interval. Fig. 1 plots the Penticton observed values of the F10.7 cm solar flux with along with a display of how the solar flux data is typically implemented by atmospheric density models used in orbit propagation. The figure shows the solar flux varies considerably from measurement to measurement and from day to day. It should be noted that the period covered in Fig. 1 is one of extreme solar activity and not typical, but these periods of extreme activity are when satellite drag effects have the largest impact on orbit determination.

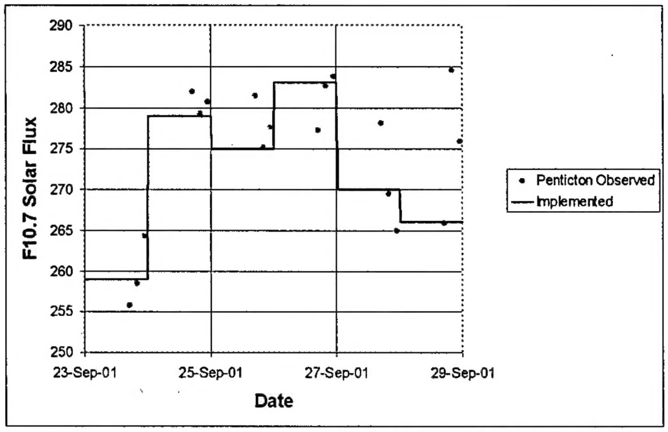


Fig. 1. Observed and Implemented F10.7 cm Solar Flux Values

Geomagnetic indices are generated in a more complex way. Several ground stations record magnetic field measurements at 1-minute intervals. The data from these stations are then combined to form a single planetary estimate of geomagnetic activity. This is done in near real time by the US Air Force, but the official archival values are processed by the NGDC. It should be noted that the Air Force and NGDC employ different measurement stations so there are often differences in the real time and archived values. The thrust of this research, however, is to examine the variations in the values. The $k_p$ geomagnetic index is calculated every three hours. Like the F10.7 cm solar flux, the value is typically implemented as a constant over the measurement interval. Unlike the solar flux, the geomagnetic index is closer to an average representation over the interval. Since the ground stations record magnetic field measurements at up to 1-minute intervals, we can compare the ground station data to the estimated 3-hour $k_p$ values. Fig. 2 shows the North component of the magnetic field variations measured at Fort Simpson, Northwest Territories, Canada and the Air Force estimated values of the $k_p$ geomagnetic index as typically implemented by an atmospheric density model used in orbit propagation. The magnetic field variation has been scaled. The figure shows that the magnetic field has a much more complex behavior than that captured by the step function representation. While the high frequency dynamics may not greatly alter atmospheric density, there are more slowly-varying aspects of the data which may be important. It should be noted that there is not a direct correlation between the Fort Simpson data and the Air Force planetary $k_p$ geomagnetic index because as stated before, the Air Force values are a results of combining observations from several different ground stations.

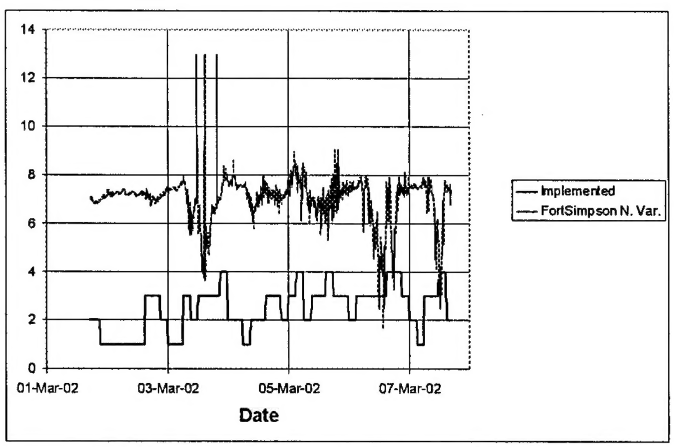


Fig. 2. Observed Magnetic Field North Component Variations and Implemented $k_p$ Geomagnetic Indices

Fig. 1 and 2 support, but do not prove, the hypothesis that the atmosphere is more variable than what is currently being implemented in atmospheric density models used in orbit propagation. The only way to effectively prove that the higher-order atmospheric density dynamics are important and should be modeled is through measurement of the density itself or the effects that it causes.

## 2.2 The Observability Hypothesis

Designing satellites to perform precise space-based measurements of atmospheric density and the chemical constituents of the atmosphere would be the obvious choice for a thorough, in-depth assault on improving knowledge of the extreme upper atmosphere. These data could then feed the theoretical development of a first principle physics-based model of the atmosphere. Practical matters such as cost, however, make this option prohibitive. A secondary option is to use the motion of known satellites to infer knowledge of atmospheric density. The second hypothesis of this research is that atmospheric density dynamics observably affect the motion of satellites. To support this hypothesis, a set of simulations were performed to compare the motion of a satellite under the influence of a "notionally varying" atmosphere against the motion of the same satellite perturbed by the standard modeling approach.

Since we have little actual knowledge of atmospheric density dynamics, but indeed that is what we seek to learn, the notionally varying atmosphere was created to provide a nearly continuous, time varying, atmospheric density conditions that could effectively serve as a "truth" model and basis of comparison. Rather than alter the formulation of an atmospheric density model, we varied the inputs to the atmospheric density model. The existing approach uses the input F10.7 cm solar flux and $k_p$ geomagnetic indices as constant values over the measurement interval. In contrast, the notionally varying atmosphere employs nearly continuous, time varying values of the input data.

Great care was taken to ensure that fair comparisons were made between the existing approach and the notionally varying model. In the notionally varying model, cubic polynomials were used to represent the time varying input data across each measurement interval. For solar radio flux, the polynomial was used to generate a varying input over one day and was constrained to be the observed solar flux value at 20:00 hours UTC; for geomagnetic indices, the cubic polynomial was used to generate a varying input over the course of three hours and was constrained such that the average of the polynomial over the three hours was the observed geomagnetic value for that three hour span. This allowed for a continuously varying atmosphere that was also consistent with the definitions of the input data parameters. If the notionally varying data were actually occurring in nature, we would expect to see the input data values observed and implemented in the existing approach. This ensures a fair comparison.

To complete the cubic polynomial formulation of the notionally varying atmosphere, three additional constraints were placed on the functions. The constraints took the form of requiring continuous zeroeth, first, and second order derivatives across measurement interval boundaries. Natural spline end conditions were placed on the ends of the data span. Several different polynomial generation strategies were employed and tested in the Matlab environment using observed solar flux and geomagnetic input data. Ultimately, we chose polynomial representations over seven measurement intervals at a time and to only use the polynomial from the center measurement interval. This produced near continuity and did not incur excessive overshoot and oscillations from interval to interval.

Once this approach was shown to be reasonable in comparison to the real measurements, it was coded into an existing orbit propagation code. The orbit code chosen was the Draper version of the Goddard Trajectory Determination System (DGTDS) for Unix. DGTDS not only gives us a propagation capability but also an ephemeris comparison, data simulation, and orbit determination capability. The software was modified to construct the notionally varying cubic polynomial coefficients at run time from the same file used to feed the existing atmospheric data models. This ensured that the same initial input proxy data would be used as input for both atmospheric models.

Four time intervals were considered in the simulation studies representing periods of low, medium, high, and extreme solar activity. During the low and medium activity periods, the notionally varying atmosphere actually became negative for short periods of time. This resulted in odd behavior, and analysis for these cases is continuing. This issue did not arise in the high and extreme solar activity periods; current results are reported from the latter cases. Fig. 3 and 4 depict the notionally varying F10.7 cm solar flux and $k_p$ geomagnetic index and also, the representation under the existing approach to atmospheric density modeling for the same data from a period of high solar activity. Fig. 5 and 6 provide the same information for a period of extreme solar activity. The implemented data sets are based on observed values of solar flux and geomagnetic indices.

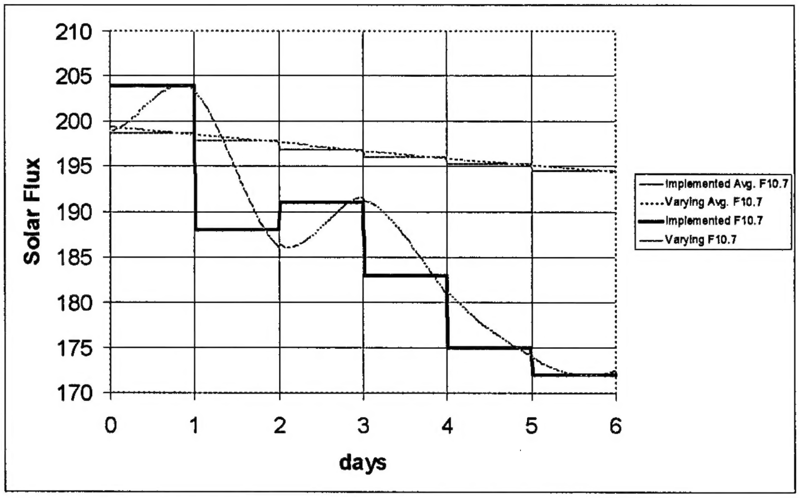


Fig. 3. Notionally Varying and Implemented F10.7 cm Solar Flux for High Solar Activity Cases

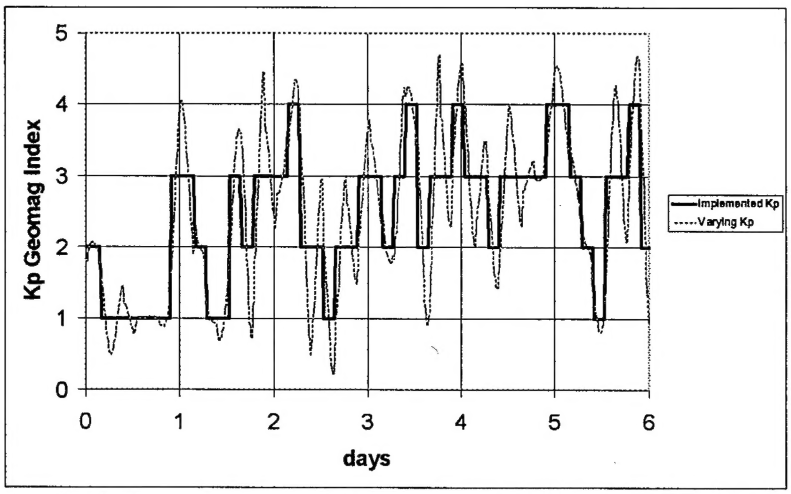


Fig. 4. Notionally Varying and Implemented $k_p$ Geomagnetic Indices for High Solar Activity Cases

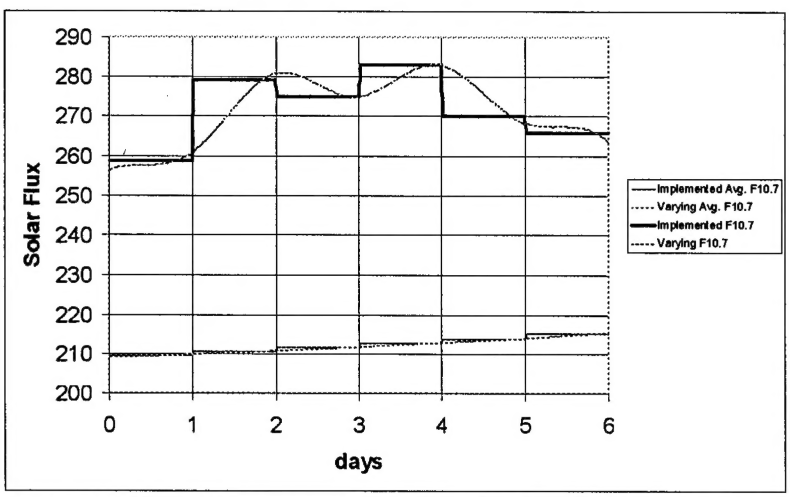


Fig. 5. Notionally Varying and Implemented F10.7 cm Solar Flux for Extreme Solar Activity Cases

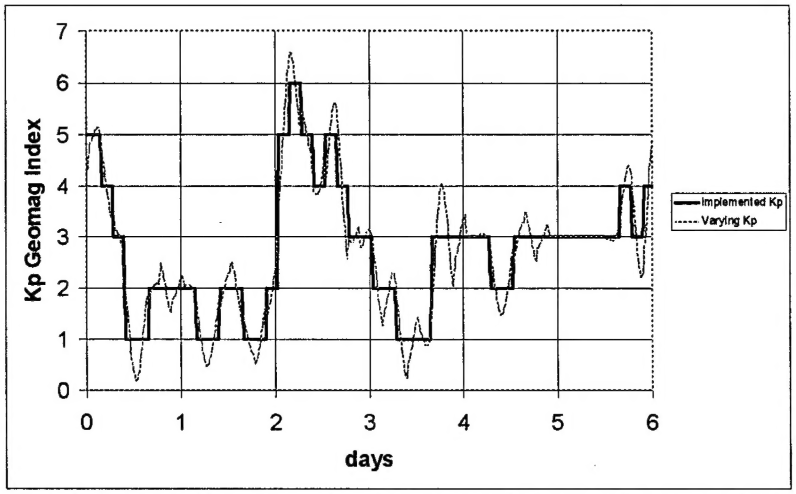


Fig. 6. Notionally Varying and Implemented $k_p$ Geomagnetic Indices for Extreme Solar Activity Cases

The first simulations were strictly ephemeris generations and comparisons. Here, orbits were propagated for six days using the notionally varying atmosphere and then the existing implementation of the atmosphere. Position was recorded every ten minutes and then compared to observe radial, cross-track, and along-track differences. The initial conditions and the force models, aside from the input data to the atmospheric density model, were exactly the same for the comparisons so that any ephemeris differences are strictly due to the effects of the modeling of the atmospheric density dynamics. Test cases included 400, 600, and 800 km altitudes. The rest of the simulation description is provided in Table I.

Table I: Simulation Description

| | | | |
|---|---|---|---|
| Altitude | 400, 600, 800 km | Geopotential | 21x21 JGM-2 |
| Eccentricity | 0.00001 | Third Body Gravity | Solar/Lunar point mass |
| Inclination | 90.0 deg | Atmospheric Density | Jacchia 70 |
| Right Ascension | 100.0 deg | Satellite Model | Sphere |
| Argument of Perigee | 270.0 deg | Cd*Area/Mass | 0.02 sq.m/kg |
| Mean Anomaly | 90.0 deg | Solar Pressure | None |
| Coordinate System | B1950.0 | Integrator | Cowell-Adams |
| Propagation Length | 6 days | Step Size | 60 sec |

Fig. 7 and 8 plot the ephemeris comparison results for the along-track component of position separation. There are small radial differences in the propagations, but these are minor in comparison with the along-track variations; cross-track differences are negligible. In the figures, differences between the notionally varying and implemented solar flux is correlated to changes in slope or acceleration in the along track differences. In both periods of solar activity, the 400 km altitude cases separate over 15 km, the 600 km cases separate around 2 km, and the 800 km cases separate over 200 m during the six-day propagations. These results state that if we had perfect knowledge of initial conditions and satellite dynamics, we would still accrue significant orbit prediction error by overlooking the atmospheric density dynamics. Of course, initial conditions are not perfectly known and satellite dynamic models, particularly those dealing with atmospheric density, are not 100% accurate, but overlooking atmospheric density dynamics may still be a major contributor to orbit prediction error.

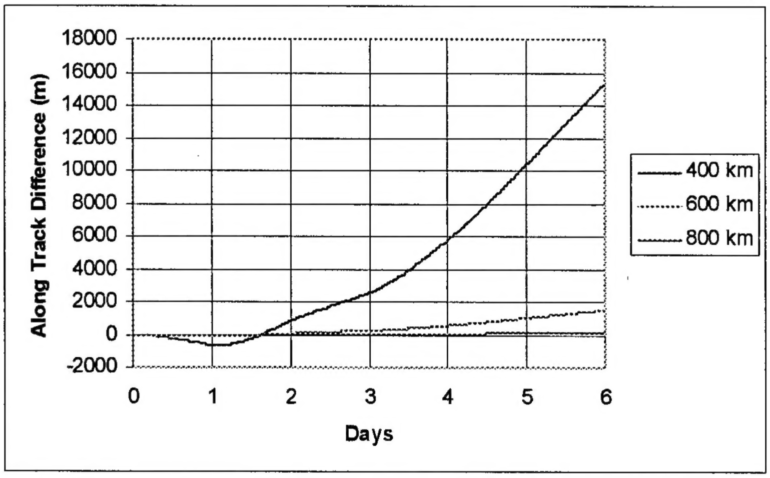


Fig. 7. Along-Track Propagation Differences for High Solar Activity

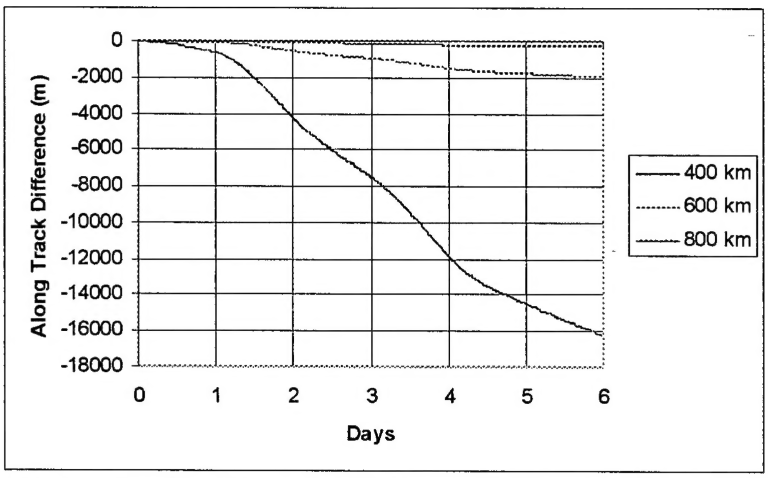


Fig. 8. Along-Track Propagation Differences for Extreme Solar Activity

After the ephemeris generation comparisons, differential corrections were performed to determine the impact of atmospheric density dynamics on orbit determination. From Fig. 7 and 8, one can see that changing the semimajor axis would account for the along-track drift in the orbit determination process. This would result in a better fit but also could drastically increase the prediction error. Like in the first simulations, propagations using the notionally varying atmosphere were considered "truth." Using the existing standard approach, a fit was made to the first three days of the truth trajectory. All six orbital elements and a drag coefficient were estimated. Following the differential correction, the estimate was propagated through the three-day fit span and a three-day prediction. The resulting orbit was compared to the truth. Fig. 9 and 10 show the differences between the estimate and reference orbits for the same periods of high and extreme solar activity described above.

As with the earlier cases, the only differences in the fit and reference orbit are the atmospheric density dynamics. In Fig. 9, for the 400 km case, there are fit span errors over 700 m. The best fit solution has changed the semimajor axis by 10 m which contributes to a prediction error growth rate in excess of 1 km/day. In the extreme solar activity case, the fit span error grows close to 3 km for the low altitude case, and the prediction error growth rate is enormous largely due to the atmospheric density dynamics and a 6 m error in the estimation of the semimajor axis. The sole source of these errors is the unmodeled atmospheric density dynamics.

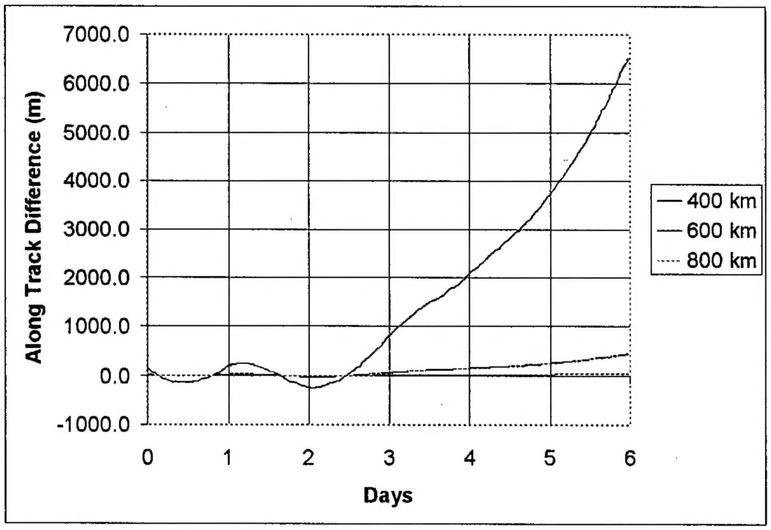


Fig. 9. Fit and Prediction Errors due to Poor Atmospheric Density Dynamics during High Solar Activity

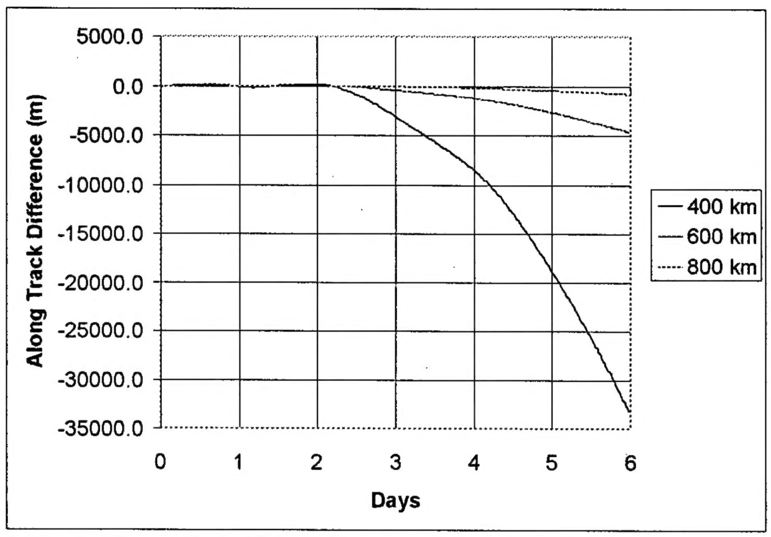


Fig. 10. Fit and Prediction Errors due to Poor Atmospheric Density Dynamics during Extreme Solar Activity

All of these simulations show that variations in atmospheric density can lead to observable effects in the motion of low earth satellites. Analysis of the simulation results reveals conclusions consistent with what intuition and physical insight tells us. First, the effects are larger at lower altitudes but can be observable upwards of 800 km altitude under some conditions. Second, the differences are larger at higher levels of solar activity; this was much more true for solar radio flux than for geomagnetic conditions. Next, the effects are larger under certain conditions such as large percent changes or a consistent change in conditions for several days in a row. These observations will help guide our search for the dynamic atmospheric effects with real world data.

While the notionally varying atmosphere is a mere construction, all of the results presented here are consistent with experience from real world orbit determination and prediction. Even the magnitudes of the orbit error are not unlike that seen in the real world under similar conditions. It is true that the existing atmospheric density models are limited in accuracy and that there are multiple sources leading to orbit prediction error, but inspection of the results presented here combined with the lessons from real world experience and the DCA work clearly indicate that atmospheric density dynamics is a major limitation of current approaches.

## 3. CONCLUSIONS AND FUTURE WORK

This research is built on two fundamental hypotheses: 1) the atmosphere is much more dynamic than what is currently being implemented in orbit propagation theory, and 2) these atmospheric density dynamics observably affect the motion of satellites. The first hypothesis finds support from ground- and space-based measurement data. The second hypothesis is sustained by real world orbit determination experience, DCA results, and particularly identified by the simulation results. The results presented along with other achievements during the initial phase of this work have major implications for the course of this research. The magnitude of the simulation differences indicates that it may be possible to observe the unmodeled dynamic atmospheric effects through the motion of known satellites using less sophisticated techniques and measurement sources than originally thought. Thus, many more satellites are possible candidates to be studied. Additionally, we may be able to take advantage of the DCA empirical estimation results to feed our theoretical development. We have observed that the solar radio flux variations play a much greater role in the satellite motion effects. This is fortuitous since we will attempt to use the motion of satellites to observe key solar effects in atmospheric heating, as represented through solar flux data in the simulations, and to use the geomagnetic indices and other geophysical observations to draw physical links to the secondary effects on the satellite motion. Most importantly, it is now clear that unmodeled atmospheric density dynamics can significantly affect the motion of satellites. This research has potential to greatly improve orbital prediction for drag-perturbed satellites.

Future work for this research will first focus on using the motion of known satellites to observe atmospheric density dynamics. This can be accomplished using DCA approaches, precise orbit determination approaches, and through on-orbit accelerometer measurements. Once this is completed and relevant atmospheric density dynamics have been characterized, the final phase of this research will attempt to link these effects with observed physical phenomena. It is hoped that this improved fundamental knowledge of the atmospheric density dynamics will enhance DCA approaches and feed the development of new physics-based atmospheric density models.


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